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# EFFECTS OF HIP CENTER LOCATION ON THE MOMENT-GENERATING CAPACITY OF THE MUSCLES

SCOTT L. DELP* and WILLIAM MALONEY†

*Departments of Biomedical Engineering and Rehabilitation Medicine, Northwestern University, and Sensory Motor Performance Program, Rehabilitation Institute of Chicago, Chicago, U.S.A. and †Palo Alto Medical Clinic, Palo Alto, California, U.S.A.

**Abstract**—We have developed a three-dimensional biomechanical model of the human lower extremity to study how the location of the hip center affects the moment-generating capacity of four muscle groups: the hip abductors, adductors, flexors, and extensors. The model computes the maximum isometric force and the resulting joint moments that each of 25 muscle–tendon complexes develops at any body position. Abduction, adduction, flexion, and extension moments calculated with the model correspond closely with isometric joint moments measured during maximum voluntary contractions. We used the model to determine (1) the hip center locations that maximize and minimize the moment-generating capacity of each muscle group and (2) the effects of superior–inferior, anterior–posterior, and medial–lateral displacement of the hip center on the moment arms, maximum isometric muscle forces, and maximum isometric moments generated by each muscle group.

We found that superior–inferior displacement of the hip center has the greatest effect on the force- and moment-generating capacity of the muscles. A 2 cm superior displacement decreases abduction force (44%), moment arm (12%), and moment (49%), while a 2 cm inferior displacement increases abduction force (20%), moment arm (7%) and moment (26%). Similarly, a 2 cm superior displacement decreases flexion force (27%), moment arm (6%), and moment (22%), while inferior displacement increases all three variables. Anterior–posterior displacement alters the moment-generating capacity of the flexors and extensors considerably, primarily due to moment arm changes. Medial–lateral displacement has a large effect on the moment-generating capacity of the adductors only. A 2 cm medial displacement decreases adduction moment arm (20%), force (26%) and moment (40%). These results demonstrate that the force- and moment-generating capacities of the muscles are sensitive to the location of the hip center.

## INTRODUCTION

The primary goals in total hip arthroplasty are to relieve pain, improve range of motion, and restore normal activity. Pain is usually relieved and range of motion improved if the prosthetic components are properly inserted and remain structurally sound (Johnston *et al.*, 1979). To perform normal activities, however, subjects must be able to generate the moments needed to execute a variety of movements. Thus, the functional result of an otherwise satisfactory hip reconstruction may be compromised if the capacity of the muscles to generate moment is greatly reduced. For example, if the hip abductors are unable to develop the moments needed to counteract the moment from body weight during single-leg stance, a limp is likely to result (Borja *et al.*, 1985; Inman, 1947; Inman *et al.*, 1981; Perry, 1985). If the hip extensors are weak, the muscles may not be able to generate the moments needed to climb stairs, or rise from a chair.

The capacity of a muscle group to generate moment about the hip depends on the force-generating capacity and moment arm of each muscle in the group. The force-generating capacity of a muscle group may be reduced if a hip reconstruction alters the length–tension relationships of the muscles in the group and thereby decreases the forces they can generate. Surgical changes may also alter the distances between the muscles and the hip center, thus changing their moment arms about the joint. Similarly, disease states of the hip, such as protrusio and dysplasia with subluxation or dislocation, change the geometric relations among the muscles and the bones. Changing the length or moment arm of a particular muscle, or number of muscles, may decrease, or increase, the moment that can be generated about the joint.

The length–tension relationship and moment arm of each muscle crossing the hip are affected by the position of the hip center. Since musculoskeletal disease, hip prosthesis design, and reconstructive surgical technique can affect the position of the hip center, it is important to understand how variations in the location of the hip center affect the potential of muscles to generate moments. The general objective of this investigation was to examine how the force- and moment-generating capacities of the hip muscles are affected by alterations of the hip center. The specific aims were:

(1) to determine the locations of the hip center that maximize and minimize the moment-generating capacity of four muscle groups (abductors, adductors, flexors, and extensors);

(2) to quantify the effects of anterior–posterior, superior–inferior, and medial–lateral displacement of

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Address correspondence to: Scott L. Delp, Ph.D., Sensory Motor Performance Program, Rehabilitation Institute of Chicago (Room 1406), 345 East Superior Street, Chicago, IL 60611, U.S.A.

the hip center on the moment arms, maximum isometric muscle forces, and maximum isometric joint moments of each muscle group.

## METHODS

We developed a computer model of the human lower extremity to study the effects of displacing the hip center on the isometric moment-generating capacity of the muscles (Delp *et al.*, 1990b). This model, which represents an adult male with a height of 1.8 m, estimates the moments that are produced at any body position when the muscles are fully excited under isometric conditions.

We studied the effects of hip center location on the hip *abductors* [gluteus medius, minimus, and maximus (anterior fibers), tensor fasciae latae, piriformis, and sartorius], *adductors* (adductor magnus, longus, and brevis, pectineus, semimembranosus, and gracilis), *extensors* [gluteus maximus, semimembranosus, semitendinosus, biceps femoris (long head) adductor magnus, gluteus medius (posterior fibers), gluteus minimus (posterior fibers)], and *flexors* [iliacus, psoas, rectus femoris, sartorius, tensor fascia latae, gluteus medius (anterior fibers), gluteus minimus (anterior fibers)]. Muscles that contribute to moments with respect to more than one axis (e.g. gluteus maximus, gluteus medius, gluteus minimus, sartorius, tensor facia latae, adductor magnus) were included in multiple muscle groups. Although we also modeled the internal and external rotators of the hip, effects on these groups are not reported here because very little experimental data (i.e. measured moment arms and joint moments) are available to test our models of these muscles.

The lines of action of 25 muscle–tendon complexes that cross the hip were defined based on their anatomical relationships to three-dimensional representations of the pelvis, femur, tibia, and patella (Fig. 1). Each muscle was described as a line segment, or a series of line segments (i.e. some muscles are constrained to pass through 'via' points between origin and insertion), that approximate the muscle's centroidal path. The kinematics of the hip and knee were characterized so that the moment arms and the origin-to-insertion length of each muscle–tendon complex can be computed for any combination of hip and knee angles. The knee model, which is based on the work of Yamaguchi and Zajac (1989), accounts for the kinematics of the tibiofemoral joint, the patellofemoral joint, and the patellar levering mechanism. The moment arm of an individual muscle ($ma_i$) for a particular degree of freedom (e.g. hip flexion) was computed as the partial derivative of the muscle's origin-to-insertion length ($l$) with respect to the joint angle (e.g. hip flexion angle) (An *et al.*, 1984). That is,

$$ma_i = \delta l / \delta \theta, \tag{1}$$

where $\theta$ is the joint angle. Since three angles ($\theta_{\text{flexion}}$, $\theta_{\text{adduction}}$, $\theta_{\text{rotation}}$) were used to characterize the orientation of the femur with respect to the pelvis, three scalar moment arms about the hip (one for each degree of freedom) were computed for each muscle at each body position. An additional moment arm for knee flexion–extension was computed for muscles that also cross the knee. The moment arms of individual muscles were calculated and compared to moment arms reported in the literature (Nemeth *et al.*, 1983) and moment arms computed from the muscle attachment coordinates described by Brand *et al.* (1982) over a range of body positions. These comparisons, combined with a detailed inspection of the muscle lines of action on the computer graphics system, were used to validate our representation of the musculoskeletal geometry.

To compute the maximum isometric joint moment, the maximum isometric muscle force generated by each muscle–tendon complex (i.e. the force developed when muscle is maximally excited under isometric conditions) must be calculated as a function of origin-to-insertion length. The isometric force-generating property of each muscle–tendon complex was derived by scaling a generic model of muscle and tendon (Zajac, 1989). Four parameters (peak isometric muscle force, optimal muscle-fiber length, tendon slack length, and pennation angle) scale the generic model to represent a specific muscle–tendon complex. Peak isometric force was estimated by multiplying the physiological cross-sectional area data reported by Brand *et al.* (1986) by a 'specific tension' of 25 N $cm^{-2}$. Optimal fiber lengths of muscles were taken from Wickiewicz *et al.* (1983) and Friederich and Brand (1990). Together, peak isometric force and optimal fiber length scale the active and passive force–length properties of muscle. Peak isometric force and tendon slack length, the length of tendon beyond which force develops (Zajac, 1989), scale the nonlinear force–length property of tendon. Pennation angle, from Wickiewicz *et al.* (1983) and Friederich and Brand (1990), specifies the angle between the tendon and the muscle fibers at optimal length. Since these four parameters were specified for each muscle–tendon complex, the maximum isometric force that each muscle generates can be computed for any combination of hip and knee angles.

The maximum isometric moment generated by each muscle was calculated by multiplying the muscle's maximum isometric force and moment arm at each hip angle. This calculation was repeated for a range of hip angles to compute the maximum isometric moment vs joint angle curve of the muscle. The maximum isometric moment vs joint angle curves for all the muscles in a group were summed to determine the maximum isometric moment vs joint angle curve of the muscle group. The maximum isometric moment vs joint angle curve calculated for each muscle group was then compared with isometric joint moments that have been measured during maximum voluntary contractions at a variety of body positions (Cahalan *et al.*, 1989; Inman *et al.*, 1981; Markhede and Grimby, 1980;

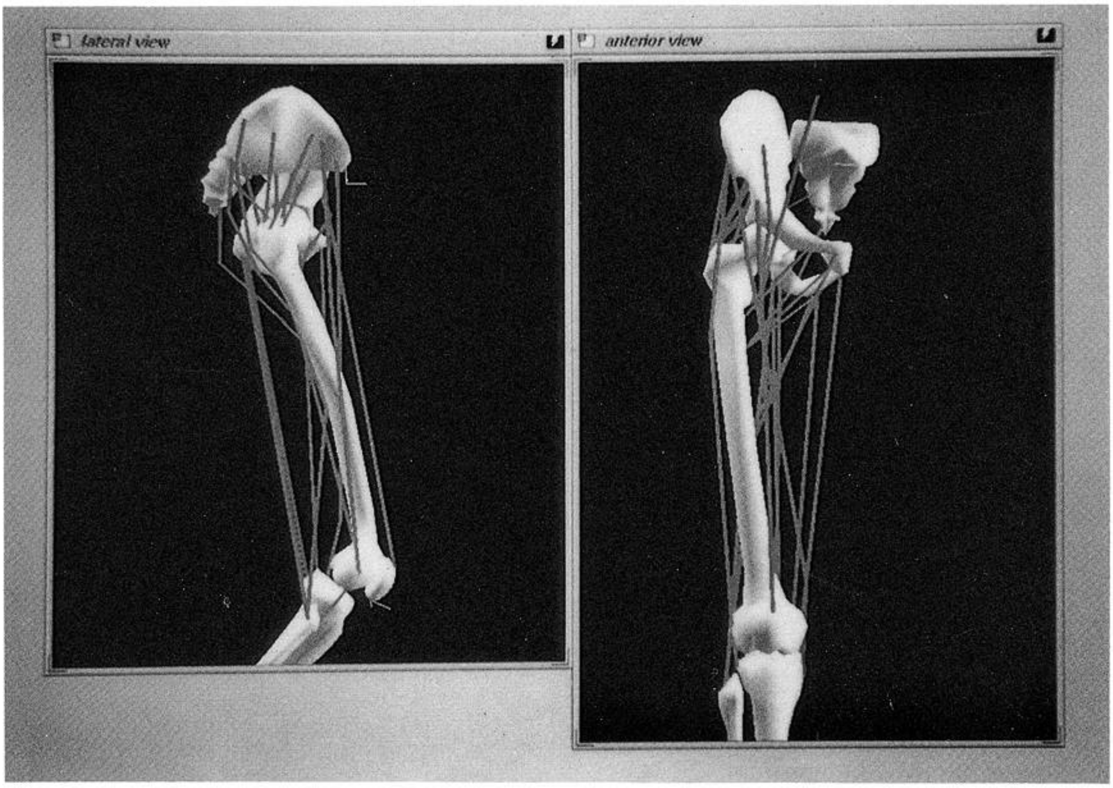


Fig. 1. Three-dimensional model used to calculate the lengths and moment arms of 25 muscle–tendon complexes crossing the hip. Since the isometric force-generating properties of each muscle–tendon complex have been characterized by specifying its peak isometric force, optimal muscle-fiber length, tendon slack length, and pennation angle, the isometric moment-generating capacity of each muscle can be estimated for a variety of body positions.

Murray and Sepic, 1968; Nemeth *et al.*, 1983; Olson *et al.*, 1972; Ryser *et al.*, 1988; Waters *et al.*, 1974).

To model displacement of the hip center, reference frames were fixed in the pelvis, femur, tibia, and patella. The center of the femoral head was considered to be the center of the hip joint. Moments were, therefore, computed about the center of the femoral head and displacements of the femur correspond to displacements of the hip center. The femur, tibia, and patella were translated relative to the pelvis by a given displacement (e.g. 1 cm superior). The relationship between the pelvis and the femur was, therefore, changed, but the relationships between the femur, tibia, and patella remained unaltered. The muscles that originate on the pelvis and insert on the femur (e.g. gluteus medius), patella (rectus femoris), and tibia (hamstrings) were displaced along with the bones; thus, their lengths and moment arms were changed by the displacement. The musculoskeletal model was used to determine how these changes in muscle lengths and moment arms affect the maximum isometric force and moment generated by each muscle group.

*Determining hip centers that maximize and minimize moment-generating capacity*

The model was used to find the positions of the hip center that maximize and minimize the average moment that can be generated by each muscle group over a specific range of motion. The ranges of motion over which the moments were averaged were based on the range of hip angles over which moments are generated during walking (Johnston, 1973; Winter, 1987), stair climbing (Andriacchi *et al.*, 1980; McFadyen and Winter, 1988) and rising from a seated position (Rodosky *et al.*, 1989), and are shown as shaded regions in Figs 3–6. The range of hip abduction angles over which adduction and abduction moments were averaged was made approximately 18° larger than the angles used during walking because the range in walking is very narrow ($\approx 12°$) This was done so that our results would take into account that adduction and abduction moments must be generated over a larger range of motion during activities that involve more lateral movement, such as exiting from a car or stepping to the side.

The position of the hip center that maximizes the average moment generated by each muscle group was determined using the following procedure. The hip center was translated to 9261 discrete positions (corresponding to 2 mm translation increments) that lie within a 2 cm displacement from the anatomical hip center in each direction (Fig. 2). This range of hip center positions includes most of the locations that could result from dysplasia, arthritic erosion, surgical reconstruction, or failed arthroplasty. At each position of the hip center, the maximum isometric moment vs joint angle curve of the muscle group was computed, as described above. The average moment generated by this muscle group ($\overline{M}$) over the specified range of joint angle ($\theta_0$–$\theta_f$) was then calculated from the maximum isometric moment vs joint angle curve using

$$\overline{M} = \frac{\sum_{\theta=\theta_0}^{\theta_f} M_\theta}{k}, \tag{2}$$

where $M_\theta$ is the maximum isometric moment generated by the muscle group at a particular joint angle, and $k$ is the number of samples of $M_\theta$ between $\theta_0$ and $\theta_f$. The position of the hip center that resulted in the greatest average moment ($\overline{M}$) was determined by comparing the average moments for all the hip center locations. Finally, the maximum isometric moment vs joint angle curve was plotted for the hip center that maximized $\overline{M}$ for the muscle group. A similar procedure was used to find the position of the hip center that minimizes $\overline{M}$.

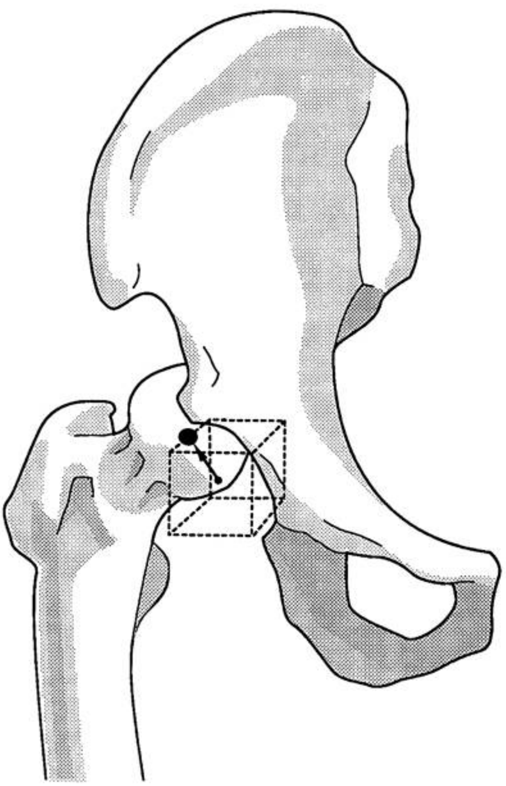

Fig. 2. Hip center (large dot) displaced 2 cm superiorly and 2 cm laterally from the anatomical hip center (small dot). The dashed cube, 4 cm on each side, shows the range of hip center locations that was investigated.

*Determining the effects of displacement on force, moment arm, and moment*

The hip center was displaced in 2 mm increments along one of the three axes (anterior–posterior, superior–inferior, and medial–lateral), while the position along the other two axes was maintained at the anatomical hip center. At each position along an axis, the average moment ($\overline{M}$), average force ($\overline{F}$), and average moment arm ($\overline{\mathrm{ma}}$) were computed for each muscle group. $\overline{M}$ was computed using equation (2). $\overline{F}$ was calculated by first summing the maximum isometric force vs joint angle curves for all muscles in a group and then computing

$$\overline{F} = \frac{\sum_{\theta=\theta_0}^{\theta_f} F_\theta}{k}, \tag{3}$$

where $F_\theta$ is the maximum isometric force generated by the muscle group at a particular joint angle, and $k$ is the number of samples of $F_\theta$ taken in the range of joint angle ($\theta_0$–$\theta_f$).

The moment arm of a muscle group (ma) for a particular degree of freedom was computed as the sum of the moment arms of each muscle ($\mathrm{ma}_i$) for that degree of freedom multiplied by the muscle's peak isometric force $(F_o^M)_i$ divided by the sum of the peak forces of all the muscles in the group. That is, for $n$ muscles,

$$\mathrm{ma} = \frac{\sum_{i=1}^{n} \mathrm{ma}_i (F_o^M)_i}{\sum_{i=1}^{n} (F_o^M)_i} \tag{4}$$

which represents a weighted average moment arm of the muscle group. The moment arm of the muscle group (ma) was plotted vs joint angle and then the average moment arm ($\overline{\mathrm{ma}}$) was calculated as

$$\overline{\mathrm{ma}} = \frac{\sum_{\theta=\theta_0}^{\theta_f} \mathrm{ma}_\theta}{k}, \tag{5}$$

where $\mathrm{ma}_\theta$ is the moment arm of the muscle group (ma) at a particular joint angle and $k$ is the number of samples of $\mathrm{ma}_\theta$ taken in the range of joint angle ($\theta_0$–$\theta_f$).

The average moment ($\overline{M}$), force ($\overline{F}$), and moment arm ($\overline{\mathrm{ma}}$) of each muscle group were plotted vs the displacement along each axis. From these plots, the percent change in $\overline{M}$, $\overline{F}$, and $\overline{\mathrm{ma}}$ with displacement was determined.

Alterations of the hip center can change the isometric moment-generating capacity of the knee flexors and extensors by altering the lengths and moment arms of the hamstrings and the rectus femoris. These effects were evaluated by computing the hip center locations that maximize and minimize the average moment ($\overline{M}$) generated by the knee flexors and extensors over a 90° range of knee motion (i.e. $\theta_0$ is full extension and $\theta_f$ 90° flexion). We also computed the change in $\overline{M}$, $\overline{F}$, and $\overline{\mathrm{ma}}$ of the knee muscles with displacement of the hip center in each direction. These computations were made with the hip flexed 0, 30, and 60°

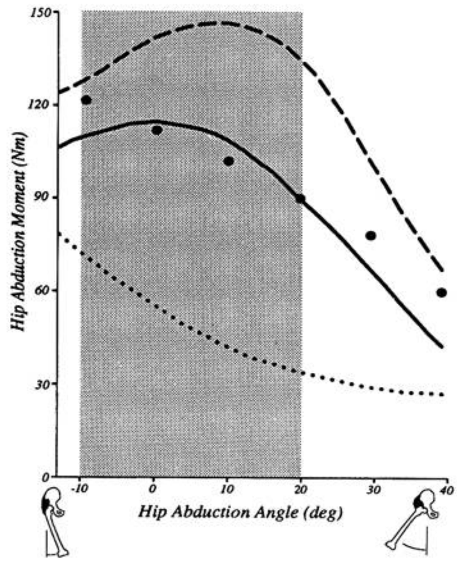


Fig. 3. Hip abduction moment vs hip abduction angle. Maximum isometric moment calculated with the anatomical hip center (solid curve) is compared with abduction moment measured by Olson *et al.* (1972, Fig. 3) during maximum voluntary contractions (dots). Hip centers were found that maximize and minimize the average moment generated over the shaded range of hip abduction angles. The maximum moment (dashed curve) resulted from displacing the hip center 2 cm inferiorly, 2 cm medially, and 1.4 cm anteriorly. The minimum moment (dotted curve) resulted from displacing the hip center 2 cm superiorly, 2 cm medially, and 1.2 cm anteriorly. Note that the locations of the hip center that maximize and minimize the moment-generating capacity of the abductors differ only by superior–inferior displacement (except for a 2 mm anterior displacement). The hip was maintained in 0° flexion and the knee was in full extension.

## RESULTS

### *Maximum and minimum joint moments*

Displacing the hip center 2 cm inferiorly, 2 cm medially, and 1.4 cm anteriorly increases hip *abduction* moment from 115 to 142 N m at 0° hip abduction (Fig. 3, cf. solid and dashed curves). This location of the hip center maximizes the average moment that can be generated by the hip abductors over the range of joint angle shaded in Fig. 3. The primary reason for the increase in moment is that inferior displacement increases both the average moment arm (7%) and the average force (20%) generated by the hip abductors. Anterior and medial displacement have relatively small effects on abduction moment compared to the effect of inferior displacement.

Displacing the hip center 2 cm superiorly, 2 cm medially, and 1.2 cm anteriorly minimizes the average moment that can be generated by the abductors over the range of joint angle shaded in Fig. 3. At 0°, abduction moment decreased from 115 to 55 N m with this displacement (cf. solid and dotted curves).

Interestingly, hip center locations that maximize and minimize the moment-generating capacity of the

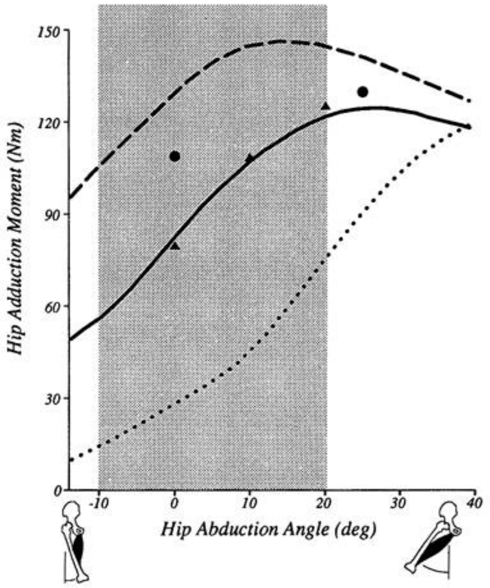


Fig. 4. Hip adduction moment vs hip abduction angle. Maximum isometric moment calculated with the anatomical hip center (solid curve) corresponds well with adduction moments measured by Cahalan *et al.* (1989, Table 4) (triangles) and Murray and Sepic (1968, Fig. 1) (dots) during maximum voluntary contractions. Hip centers were found that maximize and minimize the average moment generated over the shaded range of hip abduction angles. The maximum moment (dashed curve) resulted from displacing the hip center 1 cm inferiorly, 2 cm laterally, and 2 cm anteriorly. The minimum moment (dotted curve) resulted from displacing the hip center 2 cm superiorly, 2 cm medially, and 1.2 cm anteriorly, which is the same displacement that minimizes the moment-generating capacity of the abductors. The hip was maintained in 0° flexion and the knee was in full extension.

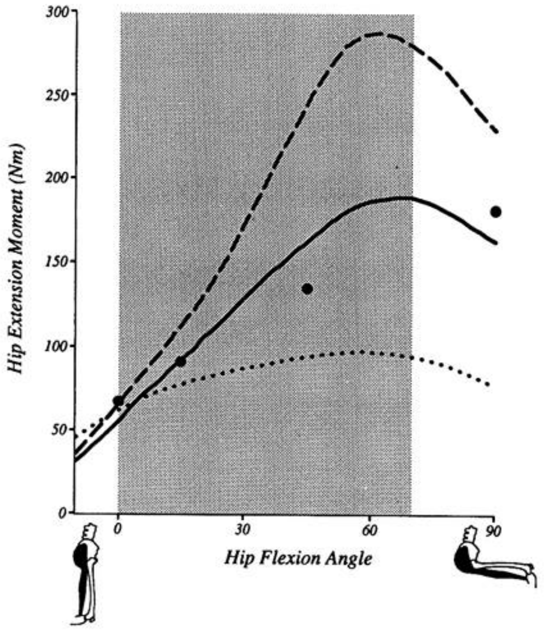


Fig. 5. Hip extension moment vs hip flexion angle. Maximum isometric moment calculated with the anatomical hip center (solid curve) is compared with extension moment measured by Waters *et al.* (1974, Chart II) during maximum voluntary contractions (dots). Hip centers were found that maximize and minimize the average moment generated over the shaded range of hip flexion angles. The maximum moment (dashed curve) resulted from displacing the hip center 2 cm anteriorly, 2 cm superiorly, and 2 cm laterally. The minimum moment (dotted curve) resulted from displacing the hip center 2 cm posteriorly, 2 cm inferiorly, and 2 cm medially. The knee was flexed 90° for both the experimental and computed moment curves. The hip was maintained in 0° abduction.

abductors differ only by superior–inferior displacement (except for a 2 mm anterior displacement, which has very little effect). When combined with superior displacement, both anterior and medial displacement reduce abduction moment by decreasing muscle length and force. In contrast, anterior and medial displacement increase the moment when combined with inferior displacement by increasing abduction moment arm. When combined with inferior displacement, force does not decrease with anterior and medial displacement because the inferior displacement is sufficient to maintain muscle length and force.

*Adduction* moment increases from 85 to 130 N m (at 0° hip abduction) from displacing the hip center 1 cm inferiorly, 2 cm laterally, and 2 cm anteriorly (Fig. 4). Moment increases primarily because lateral displacement increases both the average moment arm (22%) and the average force (14%) of the hip adductors. Adduction moment decreases from 85 to 30 N m (at 0° hip abduction) as a result of moving the hip center 2 cm superiorly, 2 cm medially, and 1.2 cm anteriorly. This is the same position that minimizes the hip abduction moment. However, medial displacement is the primary reason for the decrease in hip adduction moment since it decreases both the average force (20%) and the moment arm (26%). Superior and anterior displacement also decrease adduction moment, but less than medial displacement.

Displacing the hip center 2 cm anteriorly, 2 cm superiorly, and 2 cm laterally maximizes the average moment that can be generated by the hip *extensors* over the range of motion shaded in Fig. 5. With this displacement, the moment-generating capacity of the extensors increases from 190 to 280 N m at 60° hip flexion, the angle where the largest extension moment is needed during rising from a chair (Rodosky *et al.*, 1989). Extension moment increases primarily because anterior displacement increases both the average moment arm (24%) and the average force (11%) of the hip extensors. Superior displacement has a smaller effect on extension moment. Although a 2 cm superior displacement increases the extension moment arm (19%), it decreases the force generated by the extensors (24%). Thus, superior displacement has only a small effect on extension moment because the effects on force and moment arm are opposite. Medial and lateral displacement have very small effects on extension force, moment arm, and moment.

Extension moment decreases from 190 to 98 N m at 60° hip flexion from displacing the hip center 2 cm

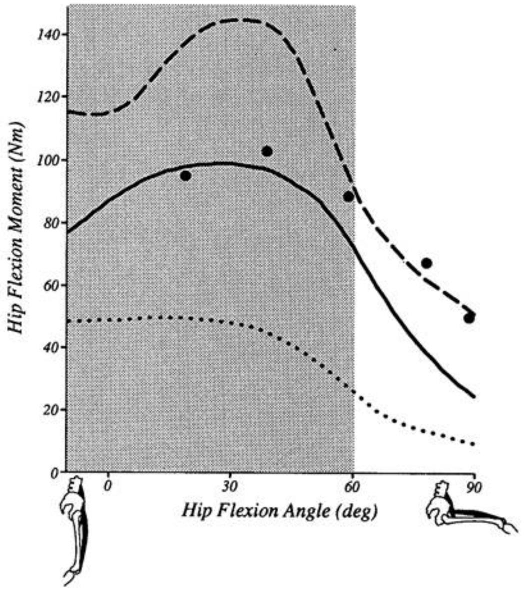


Fig. 6. Hip flexion moment vs hip flexion angle. Maximum isometric moment calculated with the anatomical hip center (solid curve) is compared with flexion moment measured by Inman *et al.* (1981, Fig. 5.13) during maximum voluntary contractions (dots). Hip centers were found that maximize and minimize the average moment generated over the shaded range of hip flexion angles. The maximum moment (dashed curve) resulted from displacing the hip center 2 cm posteriorly and 2 cm inferiorly. The minimum moment (dotted curve) resulted from displacing the hip center 2 cm anteriorly, 2 cm superiorly, and 2 cm medially. The knee was flexed 45° for both the experimental and computed moment curves. The hip was maintained in 0° abduction.

posteriorly, 2 cm inferiorly, and 2 cm medially (Fig. 5). The primary reason for the decrease in moment is that posterior displacement decreases both force and moment arm of the hip extensors.

*Flexion* moment is maximized by displacing the hip center 2 cm posteriorly and 2 cm inferiorly. This increases the moment that can be generated by the hip flexors from 98 to 142 N m at 30° hip flexion (Fig. 6). Both posterior and inferior displacement contribute significantly to the increase in moment. Posterior displacement increases flexion moment arm and inferior displacement increases force. Displacing the hip center 2 cm anteriorly, 2 cm superiorly, and 2 cm medially minimizes the average hip flexion moment. This location of the hip center decreases moment from 98 to 48 N m at 30° of hip flexion.

### *Effect of a 2 cm displacement on muscle force* ($\overline{\mathrm{F}}$), *moment arm* ($\overline{\mathrm{ma}}$), *and moment* ($\overline{\mathrm{M}}$)

Superior–inferior (SI) displacement has a large effect on all the muscle groups. A 2 cm superior displacement decreases average abduction force (44%), moment arm (12%), and moment (49%) (Table 1). This is the greatest effect that any displacement has on any muscle group. The forces and moment arms of the adductors and extensors are also affected by SI displacement. However, since force and moment arm are changed oppositely in each case (e.g. force increases but moment arm decreases), adduction and extension moments are affected only slightly. Finally, superior displacement decreases average flexion force (27%), moment arm (6%), and moment (22%), while inferior displacement increases all three variables.

Anterior–posterior (AP) displacement affects the moment-generating capacity of the flexors and extensors considerably. For the extensors, anterior displacement increases average force, moment arm, and moment. Posterior displacement has the opposite effect. For the flexors, anterior displacement slightly increases the average force, but greatly decreases moment arm. Thus, average flexion moment decreases with anterior displacement. Posterior displacement has exactly the opposite effect; it decreases force slightly, but increases moment arm greatly; so, flexion moment increases. The abductors and adductors are affected very little by AP displacement.

Medial–lateral (ML) displacement has a large effect on adduction moment only. Lateral displacement increases average adductor force (14%), moment arm (22%), and moment (40%). Medial displacement has the opposite effect. It is interesting to note that ML displacement has only a small effect on the abduction moment. Lateral displacement increases average abduction force, but decreases moment arm; thus, moment is hardly affected. Medial displacement decreases average abduction force (22%), but increases moment arm (13%); so, abduction moment is decreased by only 8% (see Table 1).

Nearly linear relations in the plots of average moment arm ($\overline{\mathrm{ma}}$) vs displacement in each direction were noted. Thus, a 1 cm displacement of the hip center results in half the change in $\overline{\mathrm{ma}}$ of a 2 cm displacement indicated in Table 1. However, the change in the average moment generated by a muscle group over a functional range of motion ($\overline{M}$) is not always linear with displacement (Fig. 7), due to the nonlinear force–length relation of muscle. For instance, abduction moment increases 18% with a 1 cm inferior displacement and 26% with a 2 cm inferior displacement, suggesting that more of the increase in abduction moment results from the first cm of inferior displacement (cf. solid curve in upper left plot). Abduction moment increases 2% with 1 cm lateral displacement, but decreases 3% with a 2 cm lateral displacement. In many other cases, however, the change in $\overline{M}$ is nearly linear with displacement.

The change in moment-generating capacity caused by displacement of the hip center along one axis can be affected by the position along the other two axes. For example, the position of the hip center along the superior–inferior axis changes the effect of medial displacement on the moment-generating capacity of the abductors. A 2 cm medial displacement of the hip center slightly decreases the moment-generating capacity of the hip abductor muscles when performed

Table 1. Percentage change in average* force ($\overline{F}$), moment arm ($\overline{\text{ma}}$), and moment ($\overline{M}$) resulting from displacement of the hip center 2 cm in each direction

| | Superior | Inferior | Anterior | Posterior | Lateral | Medial |
|---|---|---|---|---|---|---|
| *Abduction* | | | | | | |
| Muscle force† | −44 | +20 | 0 | 0 | +13 | −22 |
| Moment arm‡ | −12 | + 7 | 0 | − 3 | −14 | +13 |
| Moment§ | −49 | +26 | − 2 | +1 | − 3 | − 8 |
| *Adduction* | | | | | | |
| Muscle force† | −29 | +28 | + 2 | + 2 | +14 | −20 |
| Moment arm‡ | +15 | −13 | 0 | − 1 | +22 | −26 |
| Moment§ | −18 | +11 | + 2 | 0 | +40 | −40 |
| *Extension* | | | | | | |
| Muscle force† | −24 | +23 | +11 | −16 | + 5 | − 7 |
| Moment arm‡ | +19 | −17 | +24 | −27 | − 3 | + 2 |
| Moment§ | − 7 | 0 | +36 | −36 | + 2 | − 2 |
| *Flexion* | | | | | | |
| Muscle force† | −27 | + 4 | + 4 | − 6 | + 3 | − 4 |
| Moment arm‡ | − 6 | + 8 | −38 | +38 | − 4 | 0 |
| Moment§ | −22 | +12 | −34 | +22 | − 3 | − 3 |

* Averaged over the range of joint angles shaded in Figs 3–6; see equations (2) (3) and (5).
† Sum of the forces developed by all the muscles in a group.
‡ Average moment arm of all the muscles in the group weighted by peak isometric muscle force; see equation (4).
§ Force in each muscle multiplied by its moment arm, which is not necessarily equal to the sum of muscle forces multiplied by average moment arm of the muscle group.

alone (Table 1), greatly decreases moment-generating capacity when combined with superior displacement, but increases moment-generating capacity when combined with inferior displacement (Fig. 3).

### *Effects on knee muscles*

Alterations of the hip center can have substantial effects on the knee flexors. With the hip in neutral flexion–extension (i.e. 0° flexion), displacing the hip center 2 cm inferiorly and 2 cm anteriorly maximizes the average moment ($\overline{M}$) generated by the knee flexors and increases $\overline{M}$ 37%. The average moment decreases 38% by displacing the hip 2 cm superiorly and 2 cm anteriorly, which minimizes $\overline{M}$. The hip centers that maximize and minimize $\overline{M}$ of the knee flexors are the same for the three hip flexion angles tested (0, 30, 60°), but the changes in $\overline{M}$ are less when the hip is flexed. With the hip flexed 30°, $\overline{M}$ increases (decreases) 20% (32%) at the hip center that maximizes (minimizes) $\overline{M}$. With the hip flexed 60°, $\overline{M}$ increases (decreases) 10% (13%) at the hip center that maximizes (minimizes) $\overline{M}$.

The change in the moment-generating capacity of the knee flexors results almost entirely from alterations in muscle length. Knee flexion moment arm ($\overline{\text{ma}}$) changes less than 2% with displacement in each direction. In general, displacements that lengthen the hamstrings increase the moment-generating capacity of the knee flexors, whereas decreasing length reduces their moment-generating capacity. Thus, with the hip in 0° flexion, inferior displacement increases the average moment generated by the knee flexors, while superior displacement decreases the knee flexion moment. Anterior–posterior displacement has very little effect unless the hip is flexed beyond 20°. With 20° or more of hip flexion, anterior displacement increases the muscle length, while posterior displacement decreases the length. Medial–lateral displacement has very little effect on the moment-generating capacity of the knee flexors.

It is interesting to note that inferior displacement of the hip, which increases the moment-generating capacity of the hip abductors, adductors and flexors, also increases the moment-generating capacity of the knee flexors.

Alterations of the hip center have a very small effect on the moment-generating capacity of the knee extensors. This occurs because only the rectus femoris is affected and it is the smallest contributor to knee extension moment.

## DISCUSSION

The purpose of this study was to examine how the force- and moment-generating capacity of the muscles are affected by alterations of the hip center. Our results indicate that 2 cm changes in the location of the hip center can greatly affect the moment-generating capacity of the muscles, both by altering moment arms and muscle lengths. An important finding of this study is that displacement of the hip center along the superior–inferior axis has the greatest effect on muscle performance. Superior displacement of the hip center decreases the moment-generating capacity of the hip abductors, adductors, and flexors, while inferior displacement has the opposite effect.

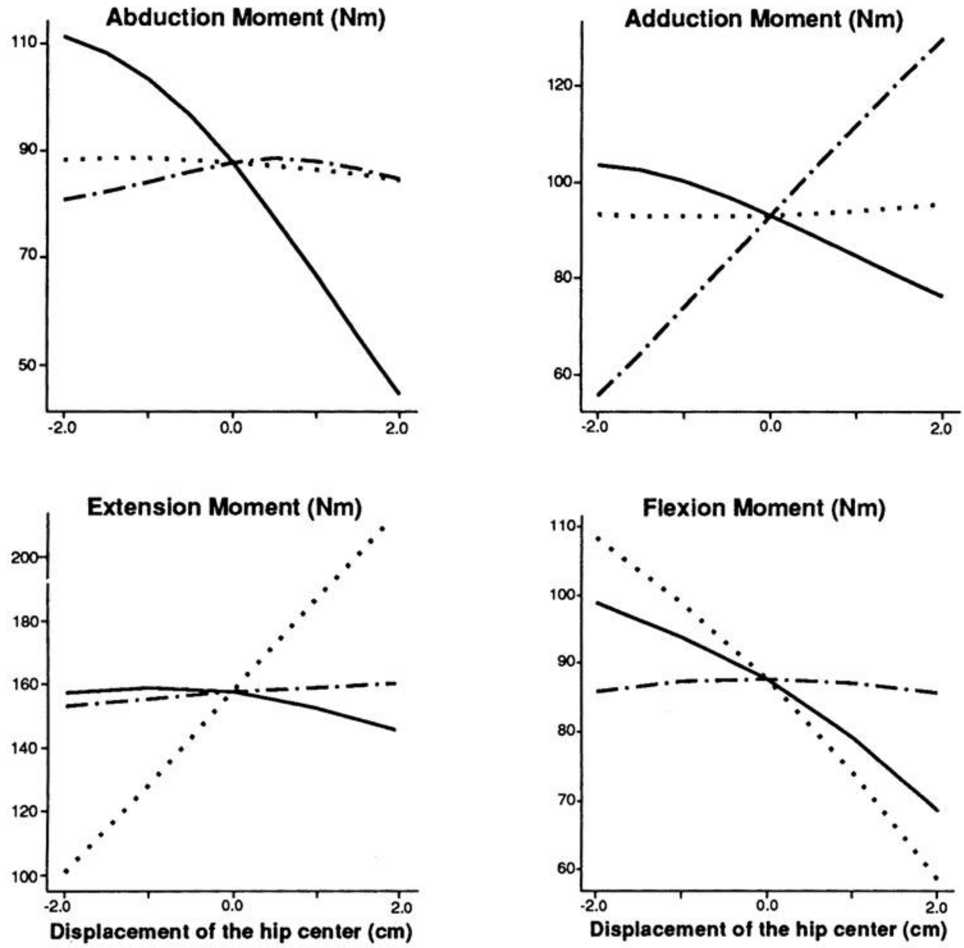


Fig. 7. Moment-generating capacity ($\overline{M}$) of each muscle group (N m) vs displacement in each direction (cm). Positive displacements indicate anterior (dotted curve), superior (solid curve) and lateral (dot–dash curve). Negative displacements indicate posterior (dotted curve), inferior (solid curve) and medial (dot–dash curve).

The effects of several assumptions should be considered when evaluating our results. First, since the femur was displaced as a unit in this study, the relationships between the femoral head, femoral neck, and greater trochanter were constant in our simulations. During hip replacement, however, these relations can be changed by choice of prosthetic components and surgical technique. For instance, a decrease in muscle length that may result from superior displacement of the hip center can be compensated by increasing the prosthesis neck length or by transferring the greater trochanter distally. In fact, there are many variables, such as orientation of the acetabular component, anteversion of the femur, and angle between the prosthetic neck and stem, that affect postsurgical geometry. We have studied the effects of one variable, the position of the hip center, while the other variables remained fixed.

Second, to test the accuracy of our model, we compared maximum isometric moments calculated using the model with isometric moments measured experimentally during maximum voluntary contractions (Figs 3–6). Comparing the model with these experimental data can be problematic since a complete, consistent set of experimental data indicating how maximum isometric hip moments vary with body position does not exist. The most complete investigation of hip muscle strength (Cahalan *et al.*, 1989) did not constrain knee motion while measuring hip moments. Other investigations report moments for only one or two muscle groups. Consequently, we had to compare our computed moments with experimental moments measured by different research groups on different subjects. For the hip abductors and adductors, several research groups report similar joint moments (Cahalan *et al.*, 1989; Murray and Sepic, 1968; Olson *et al.*, 1972). Computed adduction moments correspond closely with adduction moments measured by Murray and Sepic (1968) and Cahalan *et al.* (1989) (cf. solid curve, large dots, and triangles in Fig. 4). Computed abduction also compare well with experimentally measured abduction moments from 0 to 40° abduction (Fig. 3). However, computed moments differ somewhat from moments measured by

Olson *et al.* (1972) for abduction angles between −10 and 0°. This difference may result from underestimating the contribution of passive structures to joint moment in the model. Reported measurements of maximum extension and flexion moments vary (Cahalan *et al.*, 1989; Inman *et al.*, 1981; Kulig *et al.*, 1984; Waters *et al.*, 1974). We, therefore, compared the computed moments to moments measured under conditions that most closely match the conditions of our simulations (i.e. maximum isometric contractions with a fixed knee angle). Both computed and experimental hip extension hip extension moments peak at approximately 170 N m (cf. solid curve and large dots in Fig. 5). It is difficult to know how the experimental hip extension moment varies with hip flexion, however, given only four data points. The variation of hip flexion moment with hip flexion angle calculated with the model is consistent with the data reported by Inman *et al.* (1981) (cf. solid curve and large dots in Fig. 6). However, the peak flexion moment computed with the model is approximately 10% lower than the experimental flexion moment.

Third, we have studied the effects of hip center location on maximum isometric moments because these moments are standard measures of hip muscle strength (Cahalan *et al.*, 1989; Inman *et al.*, 1981; Markhede and Grimby, 1980; Murray and Sepic, 1968; Nemeth *et al.*, 1983; Olson *et al.*, 1972; Ryser *et al.*, 1988; Waters *et al.*, 1974). Yet, muscles are rarely activated maximally during movement. Assuming that all muscles are activated fully allows us to isolate the effects of changing musculoskeletal geometry (i.e. hip joint center) on the maximum moment-generating capacity of the muscles. It must also be noted that the maximum isometric moments calculated with our model do not correspond to the moments developed during movement when muscles are generally not isometric. In walking, the abductors contract eccentrically just after heel contact (Johnston, 1973). When rising from a chair, the hip extensors contract concentrically. Nevertheless, analysis of isometric moments can be useful. The relationship between isometric moments and concentric moments has been studied in numerous investigations (Fugl-Meyer *et al.*, 1980; Olson *et al.*, 1972; Osternig, 1986). In general, isometric and concentric moment vs joint angle curves have similar shapes and peak at approximately the same joint angles, although concentric moments are usually smaller because of force–velocity effects. While some have found that eccentric moments are larger than isometric moments (Olson *et al.*, 1972), recent evidence suggests that moments developed during maximum voluntary eccentric contractions are not statistically different from maximum isometric moments (Westing *et al.*, 1988). Data from Westing *et al.* (1990) also indicate that the joint angle where the moment peaks and the shape of the maximal moment vs joint angle curve are similar for eccentric, concentric, and isometric contractions. Therefore, quantifying how changes in the hip center affect isometric moments, by calculating the changes in moment arms and length–tension relations, helps to understand how concentric and eccentric moments are affected.

Fourth, in this study, simulations kept constant each muscle's peak isometric force, optimal fiber length, and tendon slack length. However, these parameters can change through remodeling of the muscle–tendon complex. For example, the number of sarcomeres in a muscle fiber may decrease, changing the optimal fiber length, as a muscle–tendon complex adapts to altered conditions (Williams and Goldspink, 1978). If the simulations were to allow the peak force, fiber length, and tendon length to vary, the force, moment arm, and moment calculations would all be affected.

Finally, the hip center was displaced up to 2 cm from the anatomical hip center in each direction (Fig. 2). Although this set of hip centers includes most of the possible locations that could arise from musculoskeletal disease, failed arthroplasty, or surgical reconstruction, some positions within this volume may not be feasible due to anatomical constraints (Fig. 8). The maximum and minimum moment-generating capacities shown in Figs 3–6 are affected by reducing the range of feasible hip centers. Specifically, the maximum moment-generating capacity of the hip abductors decreases 7% by restricting inferior displacement as shown in Fig. 8. The decrease is small because most of the increase in abduction moment results from the first cm of inferior displacement. Similarly, the maximum moment-generating capacity of the adductors decreased very little (4%) by restricting inferior–lateral displacement of the hip center. The minimum moment-generating capacities for the abductors and adductors are not affected because the corresponding hip centers lie within the feasible region. Since the maximum and minimum extension and flexion moments are also affected by reducing the possible hip centers, the changes in the moment-generating capacity shown in Figs 5 and 6 may be slightly exaggerated. Restricting anterior displacement, as shown in Fig. 8, reduces the maximum moment-generating capacity of the extensors 12%; restricting posterior displacement increases the minimum 10%. Similarly, restricting anterior–posterior and superior–inferior displacement of the hip center reduces the maximum moment-generating capacity of the flexors 7% and increases the minimum 10%.

Altering the moment-generating capacity of the muscles can affect function. If the capacity of a muscle group to generate moment decreases, and the group becomes unable to produce the moments required to execute a movement, a compensation, such as a limp, is likely to result. For instance, patients with weak hip abductors frequently lurch over their involved hip (Borja *et al.*, 1985; Inman *et al.*, 1981), or drop their pelvis to the contralateral side (Inman, 1947; Perry, 1985), as a result of weak abductors.

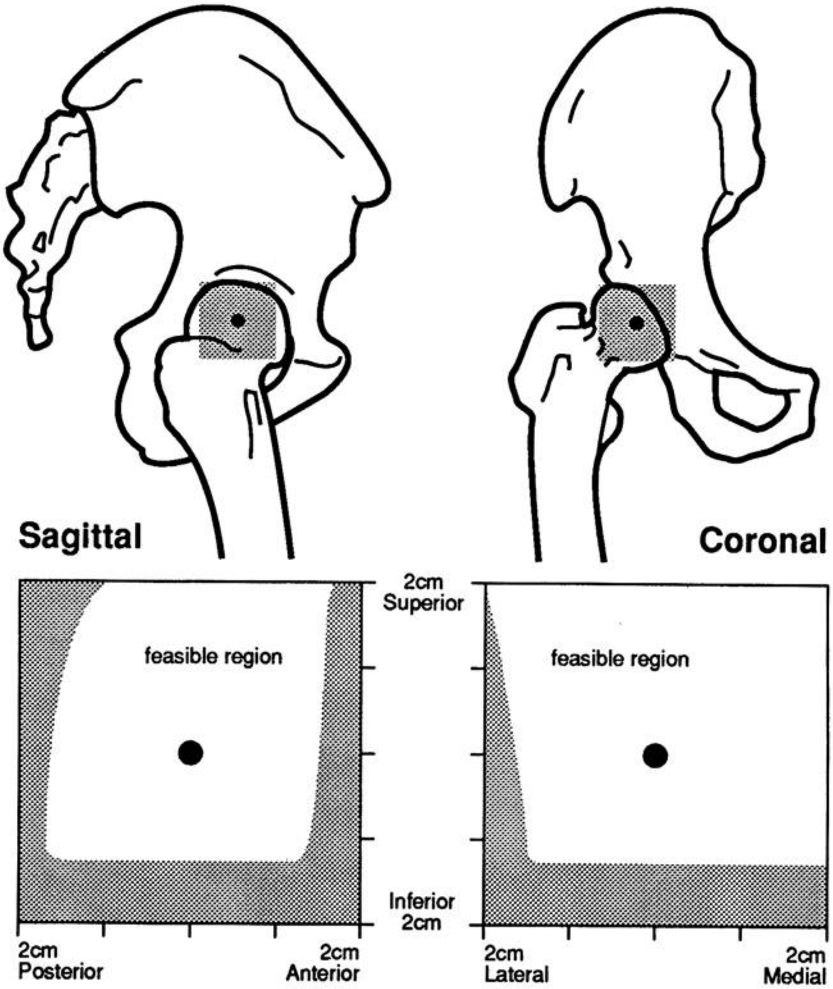


Fig. 8. Estimation of feasible hip centers. Some of the hip center locations within a 2 cm displacement in each direction from the anatomical hip center (large dot) may be infeasible (shaded area in large squares). Restricting the range of feasible hip centers can affect the magnitude of the change in moment-generating capacities of the muscles (see text for details).

How much can the moment-generating capacity of each muscle group decrease before function is compromised? The answer to this question depends on many factors that are specific to each subject; however, a general analysis can provide insight. By comparing calculations of the abduction forces and moments generated during walking (McLeish and Charnley, 1970; Winter *et al.*, 1990) to normal abduction strength (Olson *et al.*, 1972), Delp *et al.* (1990a) estimated that a 50% decrease in the moment-generating capacity of the hip abductors may be large enough to cause a limp.

The hip *extension* moments required for normal walking are relatively small (Winter, 1987); however, inverse dynamical analysis indicates that the extensors must generate a peak moment of approximately 10% of the product of body weight and height to rise from a chair without arm rests (Rodosky *et al.*, 1989). Thus, a subject with a height of 1.8 m and a weight of 70 kg must generate a peak hip extension moment of approximately 120 Nm. If it is assumed that adult males, on an average, can generate a 200 Nm hip extension moment at the hip angle where peak moment is needed (Cahalan *et al.*, 1989; Waters *et al.*, 1974), then a 50% decrease would reduce the moment-generating capacity to 100 Nm, which is less than the peak moment developed while rising from a chair.

During walking, hip *flexion* moment peaks just before toe-off, and is about one-half of peak extension moment (a 70 kg subject generates about 25 Nm of flexion moment) (Winter, 1987). While this moment-generating requirement represents only about 30% of the isometric moment-generating capacity of the flexors, greater flexion moments may be needed during other activities, such as descending stairs or rapid walking (Winter, 1987).

The few authors that have reported *adduction* moments generated during walking indicate that these moments are small (Boccardi and Pedotti, 1981; Ramakrishnan *et al.*, 1987). Comparing these estim-

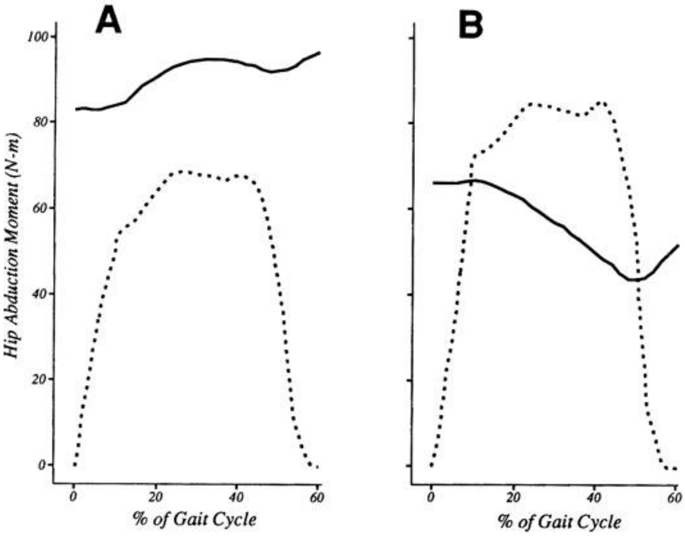


Fig. 9. Abduction moments estimated from inverse dynamics, i.e. the moment-generating *requirement* (dotted curves), compared to the maximum isometric moment-generating *capacity* of the hip abductors (solid curves). The moment-generating capacity of the abductors exceeds the moments generated during walking with the hip center in the anatomical position (A). However, displacing the hip center 2 cm superiorly, 2 cm laterally, and 1 cm posteriorly increases moment-generating requirements and decreases the moment-generating capacity, resulting in moment-generating requirements that exceed the capacity of the muscles (B). The dotted curves were taken from Johnston *et al.* (1979, Fig. 6) assuming that toe-off occurs at 60% of the gait cycle. The solid curves were obtained by computing the maximum isometric moment at hip and knee angles corresponding to normal gait (Kadaba *et al.*, 1990).

ates of the adduction moments generated during walking to isometric adduction strength measurements suggests that relatively large decreases (> 50%) in the moment-generating capacity of the adductors can be tolerated. However, larger adduction moments may be needed during activities that involve more lateral movement.

Two additional factors must be taken into account when comparing the maximum isometric moments presented here to the moment-generating requirements estimated using inverse dynamics. First, our estimates of the moment-generating potential of the muscles represent young, healthy subjects. Thus, older, arthritic patients may tolerate smaller decreases in the moment-generating capacities of the muscles than the estimates given above. Second, the position of the hip center affects not only the moment-generating *capacities* of the muscles, as reported here, but also the moment-generating *requirements* of the muscles. For instance, Johnston *et al.* (1979) showed that superior, lateral, and posterior displacement of the hip center, which often occurs as a result of osteoarthritis, can substantially increase the moments that must be generated by the hip abductors (Fig. 9). If the abductor moment-generating requirements exceed the capacity of the muscles to develop moment, an abductor lurch is likely to result.

Other displacements of the hip center may decrease moment-generating requirements. For example, medial displacement of the hip center reduces the abduction moment required to counteract gravity during single stance by decreasing the distance between body's mass center and the hip center (Johnston and Larson, 1969). Similarly, anterior displacement of the hip center may decrease the hip extension moment that must be generated during the early stance phase of gait by decreasing the anterior–posterior distance between the line of action of the ground reaction force and the hip center (Johnston *et al.*, 1979). Johnston *et al.* (1979) found that inferior, medial, and anterior positioning is the optimal location of the hip center in terms of minimizing the moment-generating requirements of the muscles. Bartel and Johnston (1969) reported similar results in an analysis of cup arthroplasty.

An important finding of our work is that inferior–medial positioning of the hip center is also desirable in terms of maintaining or improving the moment-generating capacity of the muscles. Inferior displacement increases the moment-generating capacity of the hip abductors, adductors, and flexors. Although medial displacement decreases the moment-generating capacity of the adductors, it increases abduction moment arm.

Another important finding is that a 2 cm superior displacement of the hip center substantially decreases the moment-generating capacity of the hip abductors (49%) and flexors (22%). The decrease in muscle length (force) that results from superior displacement is a major factor that contributes to this decrease in the moment-generating capacity. This suggests that it is important to compensate for decreases in muscle length (e.g. by increasing prosthetic neck length) that result from superior displacement of the hip center when a hip reconstruction is performed with a 'high hip center.'

Finally, even though the moment-generating capacity of some muscle groups can be increased by altering the location of the hip center, increases can generally be obtained only at the expense of another muscle group. Inferior displacement is a notable exception, since it increases the moment-generating capacity of three out of the four muscle groups, while the fourth group remains nearly constant.

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